Bycatch reporting in the Greenland lumpfish (*Cyclopterus lumpus*) fishery: An Analysis of 2012-2023 Data

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Authors: Søren Post & Flemming Merkel

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Introduction: The West Greenland lumpfish (*Cyclopterus lumpus*) fishery is a lucrative, short, spring fishery targeting pre-spawning females using large-meshed gillnets in shallow coastal water. As a consequence of a spatial and timely overlap with other species, there is a significant bycatch in the fishery (Merkel *et al.*, 2022). This is especially relevant for seabirds and the fishery has potential large effects on especially common eider and potentially other species such as long-tailed duck and king eider. The lumpfish fishery is MSC-certified and because the MSC-certificate is conditioned on the making improvements on several aspects related to bycatch, there are both potential economic and ecological consequences because of the bycatch. To address these issues, there is a need to obtain information on bycatch levels, possibly minimize bycatch and increase fisher compliance with relevant legislation. Unfortunately, independent observer coverage is practically absent in this small-scale fishery. Recent independent studies on bycatch suggests that bycatch is underreported, and therefore the conclusions based on the data officially reported to the authorities can rightfully be questioned (Merkel *et al.*, 2022). However, all fishers are obligated by law to report all bycatch, and this study tries to utilize this reported information. We assume that not all fishers fully comply with this requirement, but we also assume that among the >500 fishers, some will provide correct information. We refer to the latter as 'Key fishers'. If this assumption is correct, 'Key fisher' data can be used to address questions on spatial patterns in bycatch levels, which are currently not available, and temporal patterns both within and among years. This will allow for an evaluation on the ecological significance of the fishery and improve the management of it.

Method: The Greenland's Fishery License Control (GFJK) provided data on all landing events from 2012-2023. Each landing contained data on the amount of landed lumpfish roe (kg), other species landed (kg for fish, count for birds and mammals), anonymized fisher identification, catch location by spatial grid (1/4 latitude, 1/8 longitude), management area (NAFO areas 1A-1F, Fig. 1) and date.

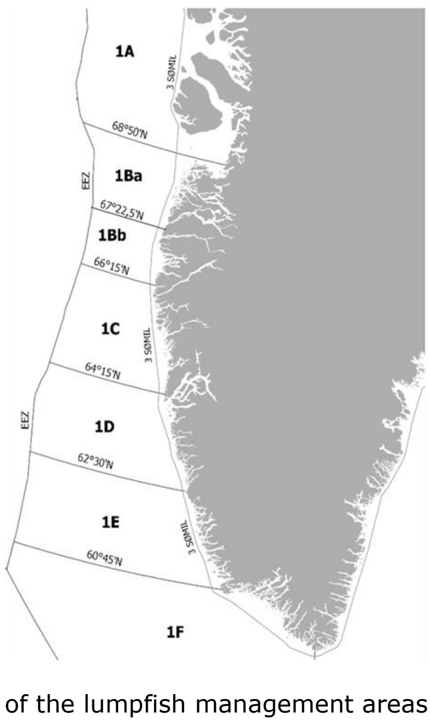

Figure 1: Map of the lumpfish management areas in West Greenland.

In total, there were 59,284 unique reported landing events from 2012-2023 in the data set. Certain landing reports, identified as unrealistic outliers, were excluded from further analyses. These included three reports of roe landings above 7,500 kg on a single day; one record with 50 common eiders (*Somateria mollissima*) and one with 115 common eiders on a single occasion, both judged unreliable; and all data from 2012–2015, during which only fish bycatch was mandatory to report. After these exclusions, a total of 34,620 landing events remained for analysis. Since 2016 all species have been included in the reporting procedure. Three wolffish species are found in Greenland waters, and all three were reported in the lumpfish fishery. Only one species, the spotted wolffish (*Anarhichas minor*), has a depth distribution that overlaps with the fishery, so it is likely that most of the reported wolffish are spotted wolffish. However, as the species could not be confirmed without direct observation, all wolffish were categorized as wolffish spp. Redfish (*Sebastes* spp.) are notoriously difficult to assign at a species level, so all redfish were combined as "Redfish spp." Similarly, other combined categories were "Rays" and "Sculpins".

Further filtering was done to investigate the general reporting of 'Core fishers', constituting only commercial fishers, and then the subgroup of 'Key fishers', which were assumed to provide a more detailed reporting of the bycatch. This filtering was done using a series of criteria for the fishers.

1. Active for at least two years between 2016 and 2023, resulting in 33,535 remaining reports. This criterion was applied to exclude fishers who had just started or stopped fishing after a single year, as such fishers were expected to have a steep learning curve and potentially different catch rates than more experienced fishers.
2. A total catch of more than 1 ton of lumpfish roe during the 2016–2023 period, leaving 32,894 reports. The lumpfish fishery has been lucrative and open to recreational fishers, who are generally inexperienced, tend to land small amounts, and may not be fully familiar with the legislation.
3. Reported at least 2 kg of bycatch from 2016–2023, leaving 16,480 reports. Previous studies on bycatch in this fishery (e.g., Merkel et al., 2022) indicate that bycatch is common. Fishers who did not report any bycatch are likely not adhering to the reporting requirements.

After this filtering of data, the data comprised the 'Core fishers' data, which included 290 individual fishers. Of these, several fishers have been active in more than one management area over the years, bringing the total "management area-fisher ID" combinations to 475.

The final panel of 'Key fishers' was selected from this group. To select the 'Key fishers', we balanced between getting enough fishers to have data to reflect actual bycatch, but at the same time not including sub-par fishers, that do not report all bycatch. We did not limit the selection to a specific number of 'Key fishers', but the initial data scrutiny led to the conclusion, that it would not be possible to obtain more than four fishers from any of the seven management areas, and not even so in most cases. This was based on the frequency of bycatch registered with the landing events, and the type of bycatch. For instance, many fishers only registered bycatch, that could be sold at the landing sites (i.e., commercial fish species). Other fishers only registered bycatch on a few occasions but mainly had "zero bycatch" events across years and days. Finally, from the remaining fishers we selected those that reported bycatch in several years in non-negligible amounts and not limited to commercial species. In table 1 the number of 'Key fishers' selected from each management area are shown.

Table 1: 'Key fishers' from each management area, the number of landing events for each 'Key fisher' from 2016-2023 and the total number of years in which the 'Key fishers' were active between 2016-2023. For each management area, the number of fishers available for 'Key fisher' selection is given in parentheses.

Management area	Fisher ID no.	No. of landing events	No. of years with data (2016-2023)
1A (N=26)	596	70	8
	640	77	8
	692	61	7
1Ba (N=43)	962	27	4
	1126	22	6
1Bb (N=26)	242	59	8
	661	85	8
	1244	148	8
	1275	106	8
1C (N=164)	153	112	8
	612	123	8
	788	102	7
1D (N=123)	590	109	8
	814	127	8
	1280	81	8
1E (N=59)	734	46	5
	885	120	8
	1109	80	7
1F (N=34)	318	61	8
	878	45	4
	1265	55	6
Total (N=475)	21	1,716	

We decided to focus on comparing areas, years, and within-year variation in bycatch, as well as estimating the total bycatch, using catch-per-unit-effort (CPUE) for the relevant species. We selected species that were either the most common or of particular interest from a Marine Stewardship Council (MSC) perspective. These species included: Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), wolffish spp., common eider, king eider (*Somateria spectabilis*), long-tailed duck (*Clangula hyemalis*), and black guillemot (*Cepphus grylle*). For each landing event, we calculated the CPUE for these species using the following equation:

$$\mathrm{CPUE_{fish}} = 100 * \frac{\text{Reported bycatch (kg)}}{\text{Reported lumpfish roe (kg)}}$$

and

$$\mathrm{CPUE_{birds}} = 100 * \frac{\text{Reported bycatch (count)}}{\text{Reported lumpfish roe (kg)}}$$

These calculations represent the kilograms of bycatch (for fish) or the number of bycaught birds per 100 kilograms of lumpfish roe. Each observation was given equal weight, and the means presented in the results section reflect the averages of all individual landing CPUEs.

We tested different hypotheses:

1. 'Key fishers' report a higher proportion of bycatch relative to roe landings compared to 'Core fishers'.
2. Bycatch CPUE for the most common bycatch species differs between management areas. This is based on varying distribution patterns across regions of the bycatch species.
3. Bycatch CPUE differs between years. The timing of seabird spring migration changes between years, as does the local distribution and this may affect the CPUEs.
4. Bycatch CPUE changes during fishing seasons. As seabirds leave the wintering grounds, the CPUE may gradually decline as fewer birds are present. Birds may also change behavior throughout the season which can influence the CPUE.
5. Key fisher' CPUE can provide quantitatively valid estimates of bycatch. A validation of their reporting was done by comparing the 'Key fisher' CPUE with in situ studies previously conducted in management area 1D.

The data on bycatch was not equally distributed between years. Seabirds are the bycatch of most concern from an ecological perspective and also in relation to the MSC-certificate for this fishery. For common eider 38% of the total bycatch, was reported in 2021. In comparison, 10% were reported from 2016-2019 combined. So, for some analyses, we focused solely on 2021. This was also a year with a public campaign regarding the need (and obligation) of fishers to report their bycatch and we considered this the year most likely to reflect the actual bycatch. Additionally, detailed in-situ studies on bycatch were conducted in 2019 and 2021, offering a basis for comparing reported bycatch with interdependent field observations.

Ordinal logistic regression (OLR) was employed to test the hypotheses using the ordinal R package (Christensen, 2023). The variables 'Year' and 'Management area' (NAFO divisions) were treated as factors. This method combines the flexibility of non-parametric approaches with the advantage of accommodating multiple variables and ordered categorical responses.

Model significance was evaluated using the Wald test (lmtest package; Zeileis and Hothorn, 2002), which tested the overall effect of the management area factor. Post-hoc pairwise comparisons between management areas were conducted using the emmeans function (emmeans package; Lenth, 2023) with Tukey's adjustment for multiple comparisons. This allowed for the identification of specific significant differences in CPUE between NAFO divisions.

Results and Discussion:

Hypothesis 1: 'Key fishers' report a higher proportion of bycatch relative to roe landings compared to 'Core fishers'.

All bycatch registered by 'Core fishers' is presented by management area in table 2. The data is displayed by weight for 'Fish' (except Greenland shark) and by count for 'Birds' and 'Mammals'. While blue whiting (*Micromesistius poutassou*) and capelin (*Mallotus villosus*) were also reported, they are excluded from the table as they are likely misreported due to their small size. Blue whiting, is mostly found in deep waters, making its presence in this coastal shallow water fishery highly unlikely and suggesting a reporting error. To facilitate a comparison with bycatch from 'Key fishers', we calculate the promille (‰) contribution of each bycatch group relative to the total lumpfish roe landings by 'Core fishers':

$$Bycatch\ proportion\ (‰) = 1000 * \frac{Bycatch\ weight\ (t)}{Lumpfish\ roe\ weight\ (t)}$$

Few fish species were reported across all management areas, with wolffish spp., Atlantic cod, and Greenland cod being the only ones. Atlantic halibut was reported in all areas except one. Of these species, wolffish spp., Atlantic cod, and Atlantic halibut are commercial that fishers can land and sell at landing sites, where they are reported to the authorities (similar to lumpfish roe). These species can therefore be considered the most reliably reported bycatch. However, there are occasions when these commercial species are not landed, either because landing sites do not always permit landings or because they are used for self-consumption. As such, the official reports should be considered as minimum estimates. Greenland cod, in contrast, is not a commercial species but was still reported in all areas.

Among the 'Birds', only the common eider is consistently reported across management areas. In contrast, a large number of king eiders (N = 177) were reported from 1Bb, but exclusively in 2020. These reports stem from four separate events, raising questions about whether they reflect an unusually high presence of king eiders that year or are misreporting's. However, the reports align well with previous aerial surveys in Southwest Greenland, which have identified the region around 1Ba and 1Bb as a high-density wintering area for king eiders (Merkel *et al.*, 2002, 2019). Possible misidentification between king- and common eider, is also a factor that cannot be ruled out. The two species' females look very similar and can lead to misidentification, especially if the eiders have been fed on by crustaceans after being caught in the net (Merkel, 2004).

In the southern part of the area (Management areas 1E and 1F), seals are reported more frequently and have a higher bycatch CPUE compared to further north. This does not align well with the general distribution of ring seal (*Pusa hispida*), the most reported seal species. The increased reporting frequency is not due to isolated outlier events, as the frequency of reports was relatively consistent. Therefore, we have no clear explanation for this discrepancy, other than the possibility of a high local abundance of ring seals that we are unaware of, or that fishers in other regions may also catch ring seals but do not report them.

Harbour porpoises (*Phocoena phocoena*) were only reported in 1Bb (N=10), but all individuals were recorded in a single event, and there are no other reports of harbour porpoises from the area between 2016 and 2023. While it is not entirely unlikely for a harbour porpoise to be caught in this fishery, they do usually not travel in large groups (Hammond *et al.*, 2002). Therefore, we consider this to be either a misreport or an incorrect species identification.

Table 3 presents all bycatch reported by 'Key fishers'. We assume that, if there is no difference between 'Core fishers' and 'Key fishers' in their tendency to report bycatch, the bycatch promille should be the same for both groups. Across the management areas, 'Key fishers' account for 10% of the total lumpfish roe catch reported (Table 4). For the commercially relevant 'Fish' groups -

namely, wolffish spp., Atlantic halibut, and Atlantic cod - the first two are not overrepresented in the 'Key fishers' data, which is expected, since there should be no difference in a fisher's motivation to land bycatch with commercial value. However, for Atlantic cod, the 'Key fishers' generally catch a higher proportion (Table 4), though we are unable to explain why. For rarer 'Fish' species, such as polar cod and Greenland shark, which are only registered on a few occasions and could easily be missed if selecting a limited group, the 'Key fishers' show a lower proportion.

Due to the lack of economic significance associated with the 'Birds' and 'Mammals' groups, these groups are particularly useful in evaluating whether 'Key fishers' are more or less likely to provide accurate bycatch estimates. Table 3 presents all bycatch reported by 'Key fishers'. For instance, the relative reporting of common eider by 'Key fishers' is significantly higher than the 10% proportion of lumpfish roe landings, with 30% of common eider bycatch being reported by 'Key fishers'. This trend is consistent across management areas, with proportions as follows: 1A (74%), 1Ba (16%), 1Bb (86%), 1C (6%), 1D (22%), 1E (30%), and 1F (31%). In area 1C, the 'Key fishers' reported only 6% of the common eider bycatch, but they also accounted for just 5% of the lumpfish roe landings in this area, reflecting a similar level of reporting bycatch in relation to lumpfish roe landings. For other relatively common bird species, such as king eider, black guillemot, long-tailed duck, and great cormorant, the bycatch reporting by 'Key fishers' also exceeds the proportion of lumpfish roe landings (Table 4). For rarer species, the proportion reported by 'Key fishers' is either 0% or 100%, reflecting the nature of selecting a limited group of fishers.

For 'Mammals', a different reporting pattern emerges. The vast majority of mammal bycatch is registered in the southern management areas, 1E and 1F. Of the 120 ring seals reported in these areas, only 5 were reported by 'Key fishers'. For harp seal (*Pagophilus groenlandicus*) and harbour porpoise in the same management areas, the 'Key fishers' reported a single harp seal bycatch, whereas 'Core fishers' reported 23 and 3 individuals, respectively. This discrepancy is likely influenced by the composition of the 'Key fisher' group, as our selection excluded the two fishers with the highest ring seal bycatch. These fishers were active for only one year during the period analyzed. If the reported bycatch by these fishers is accurate, it could be attributed to their inexperience with the area, possibly leading to unintentional net setting in a high-density seal area. Alternatively, their unfamiliarity with the reporting system might also explain the higher reported bycatch. Regardless, the 'Key fisher' selection likely offers a more consistent and representative picture of bycatch across years. However, it is important to note that annual variations, as well as rare and large catch events, may not be fully captured by this subset of fishers.

In conclusion, 'Key fishers' appear more likely to report bycatch than the average fisher, and their data provide a higher and likely more accurate estimate of the bycatch for commonly caught groups. However, this dataset reflects fishers with the highest bycatch, who may not be fully representative of the broader fishing population. Recent studies on bycatch in Greenland (Merkel *et al.*, 2022) indicate that bycatch occurs in nearly all net settings, regardless of location or individual fisher. This suggests that the low bycatch prevalence reported by the total fishery is likely due to widespread underreporting. The results also demonstrate that 'Key fishers' are less reliable for assessing bycatch of rarer species, where a substantial effort is required to capture even a single individual. Consequently, while 'Key fishers' provide valuable insights into commonly caught bycatch species, additional data collection strategies may be necessary to better understand bycatch dynamics for rarer species.

Table 2: Total reported catch from 'Core fishers' by management area (2016-2023). Note that lumpfish roe landings are shown as ton. Total landings by 'Core fishers' are approximately 50 % of the total roe landings. Greenland shark weight was assumed to be 300 kg when calculating Total and bycatch (‰).

Group	**Management area**							**Total**	**Bycatch ‰**
Fish (kg)	1A	1Ba	1Bb	1C	1D	1E	1F		
Lumpfish roe (t)	133	202	192	1,641	1,643	540	290	4,640	
Wolffish spp.	145	1,189	949	5,219	5,908	14	167	13,589	2.93‰
Atlantic cod	91	504	1,677	2,528	1,101	2,437	315	8,654	1.86‰
Atlantic halibut	218	0	259	665	1,523	330	116	3,111	0.67‰
Greenland cod	216	188	87	12	1	31	184	718	0.15‰
Redfish spp.	0	0	0	0	7	106	35	148	0.03‰
American plaice	0	0	18	1	0	7	23	49	0.01‰
Rays	0	0	4	0	0	32	4	40	0.01‰
Sculpins	0	0	6	0	0	4	2	12	0.00‰
Polar cod	0	0	0	0	0	0	3	3	0.00‰
Greenland shark (no)	0	0	0	1	0	0	0	300	0.06‰
Birds (no)									
Common eider	19	32	271	500	459	307	472	2,060	0.44‰
King eider	3	0	177	8	4	0	0	192	0.04‰
Black guillemot	2	12	5	5	0	0	9	33	0.01‰
Long-tailed duck	0	0	1	4	2	4	1	12	0.00‰
Great cormorant	0	3	0	0	0	0	0	3	0.00‰
Northern fulmar	0	0	0	3	0	0	0	3	0.00‰
Greater shearwater	0	0	0	0	1	0	0	1	0.00‰
Common loon	0	0	1	0	0	0	0	1	0.00‰
Mammals (no)									
Ring seal	2	2	7	7	11	36	84	149	0.03‰
Harp seal	0	0	0	1	2	6	17	26	0.01‰
Harbour porpoise	0	0	10	0	0	2	1	13	0.00‰

Table 3: Total reported catch from 'Key fishers' by management area (2016-2023). Note that lumpfish roe landings are shown as ton.

Group	Management area							Total	Bycatch ‰
Fish (kg)	1A	1Ba	1Bb	1C	1D	1E	1F		
Lumpfish roe (ton)	70	3	65	99	103	69	37	447 t	
Wolffish spp.	10	0	669	17	235	0	11	942	2.11‰
Atlantic cod	0	0	1417	381	21	200	49	2067	4.63‰
Atlantic halibut	0	0	207	0	24	0	41	272	0.61‰
Greenland cod	6	75	84	10	0	12	37	222	0.50‰
Redfish spp.	0	0	0	0	0	0	35	35	0.08‰
American plaice	0	0	15	0	0	7	18	40	0.09‰
Rays	0	0	0	0	0	32	4	36	0.08‰
Sculpins	0	0	1	0	0	2	2	5	0.01‰
Polar cod	0	0	0	0	0	0	0	0	0.00‰
Greenland shark (no)	0	0	0	0	0	0	0	0	0.00‰
Birds (no)									
Common eider	14	5	233	32	103	93	145	625	1.40‰
King eider	3	0	4	0	0	0	0	7	0.02‰
Black guillemot	2	2	2	0	0	0	2	8	0.02‰
Long-tailed duck	0	0	1	1	0	0	0	2	0.00‰
Great cormorant	0	1	0	0	0	0	0	1	0.00‰
Northern fulmar	0	0	0	0	0	0	0	0	0.00‰
Greater shearwater	0	0	0	0	0	0	0	0	0.00‰
Common loon	0	0	1	0	0	0	0	1	0.00‰
Mammals (no)									
Ring seal	1	0	2	0	0	1	4	8	0.02‰
Harp seal	0	0	0	0	0	0	1	1	0.00‰
Harbour porpoise	0	0	0	0	0	0	0	0	0.00‰

Table 4: The share of the total catch taken by 'Key fishers' in relation to 'Core fishers' for all categories.

'Key fisher' share of total catch					
Fish		**Birds**		**Mammals**	
Lumpfish roe:	10%	*Common eider:*	30%	*Ring seal:*	5%
Wolffish spp.:	7%	*King eider:*	4%	*Harp seal:*	0%
Atlantic cod:	24%	*Black guillemot:*	24%	*Harbour porpoise:*	0%
Atlantic halibut:	9%	*Long-tailed duck:*	17%		
Greenland cod:	31%	*Great cormorant:*	33%		
Redfish spp.:	24%	*Northern fulmar:*	0%		
American plaice:	81%	*Greater shearwater:*	0%		
Rays:	90%	*Common loon:*	100%		
Sculpins :	42%		100%		
Polar cod:	0%				
Greenland shark:	0%				

Hypothesis 2: The CPUE for the most common bycatch species differs between management areas.

We focus on 'Key fishers,' starting with common eider, the most frequently reported bycatch species. A significant difference in CPUE between management areas was observed (OLR, $P < 0.001$), with management areas 1Bb and 1F showing the highest CPUE values: 0.56 ± 0.18 and 0.79 ± 0.30 (mean ± SE, common eider per 100 kg lumpfish roe), respectively, when considering all years (Fig. 2). However, there is also a pronounced year effect (OLR, $P < 0.001$). The years prior to 2021 were characterized by generally low CPUE values, with occasional high values in isolated areas (Fig. 3). Notably, 2021 is the only year with bycatch reports from all management areas, coinciding with a pre-season campaign. This campaign, which included reminders via radio, TV ads, and outreach at landing sites, emphasized the importance and legal requirement of reporting bycatch. Thus, 2021 likely provides the most comprehensive dataset for exploring potential differences in CPUE across management areas.

In 2021, the mean CPUE for common eider was 0.74 (common eiders per 100 kg lumpfish roe; Fig. 3). The management area-specific CPUE patterns mirrored the overall trend observed across all years, with the highest values recorded in 1Bb (2.22 ± 0.94) and 1F (0.97 ± 0.40). All other areas showed lower but above-zero values. All other areas showed lower but above-zero values. The differences in CPUE between management areas were statistically significant (OLR, $P = 0.0043$). This result was mainly driven by the distinctly higher CPUE in management area 1Bb, which showed significant differences compared to 1C, 1D, 1E, and 1F (Tukey post-hoc tests, $P < 0.04$, Table 5). In contrast, CPUE values in the other areas did not significantly differ from one another (Tukey post-hoc tests, $P>0.64$). The high CPUE in 1Bb during 2021 was influenced by two large landing events where 20 and 24 common eiders were reported, contributing to 44 out of the 100 total common eiders reported that year. By contrast, common eider bycatch is typically reported as zero, occasionally 1–5 birds, and rarely more than five (Fig. 4). If these two large bycatch events are excluded, the mean CPUE for 1Bb decreases to 0.48 ± 0.17, aligning closely with the CPUE values in other areas. This pattern of elevated CPUE for common eider in 1Bb was also observed in 2022 and 2023. However, there appears to be a decline in bycatch reporting awareness compared to 2021, or 2021 may have been an exceptional year with higher bycatch rates along the coast. Nevertheless, results from Merkel *et al.* (2022) suggest that the bycatch of common eider in 2021 was likely lower than in 2019, at least in area 1D. Despite this uncertainty, there is no compelling reason to exclude the two large observations in 1Bb. As lumpfish roe landings in 1Bb are relatively small, these events will have a limited impact on the overall bycatch estimates when accounting for area-specific bycatch rates.

*Table 5: Post-hoc Tukey test results for pairwise comparisons between management areas using 'Key fishers' 2021 data. The table includes estimates, standard errors, z-ratios, and adjusted p-values. An * indicates p < 0.05.*

Contrast	Estimate	SE	z.ratio	p.value
1A - 1Ba	-0.5814	0.872	-0.667	0.9943
1A - 1Bb	-1.8302	0.652	-2.806	0.0743
1A - 1C	-0.17	0.669	-0.254	1
1A - 1D	-0.3247	0.653	-0.498	0.9989
1A - 1E	-0.1378	0.698	-0.198	1
1A - 1F	0.0337	0.715	0.047	1
1Ba - 1Bb	-1.2489	0.753	-1.66	0.6432
1Ba - 1C	0.4114	0.77	0.534	0.9983
1Ba - 1D	0.2567	0.756	0.34	0.9999
1Ba - 1E	0.4436	0.795	0.558	0.9979
1Ba - 1F	0.6151	0.811	0.758	0.9887
1Bb - 1C	1.6603	0.508	3.269	0.0186*
1Bb - 1D	1.5056	0.486	3.099	0.0319*
1Bb - 1E	1.6925	0.545	3.106	0.0312*
1Bb - 1F	1.864	0.569	3.275	0.0182*
1C - 1D	-0.1547	0.509	-0.304	0.9999
1C - 1E	0.0322	0.566	0.057	1
1C - 1F	0.2037	0.587	0.347	0.9999
1D - 1E	0.1869	0.546	0.342	0.9999
1D - 1F	0.3584	0.569	0.63	0.9959
1E - 1F	0.1715	0.62	0.277	1

Only seven king eiders were reported by 'Key fishers' across all years, making conclusions about their bycatch patterns highly uncertain. Notably, all reports were from the northern management areas, aligning with their general winter distribution (Merkel *et al.*, 2019). However, studies indicate that king eiders are also caught further south, both in commercial fisheries and trial lumpfish fisheries conducted by GINR, though with high interannual variation (Merkel, 2004; Merkel *et al.*, 2022; Post *et al.*, 2023, 2024). Other bird and mammal species were generally reported in low numbers, limiting evaluation of management area differences beyond simple presence-absence patterns (see Table 3).

For most 'Fish', it was challenging to evaluate management area differences using the 'Key fisher' data. Wolffish spp. was the most prevalent group by weight among 'Core fishers' and the second most prevalent among 'Key fishers' (Tables 2 and 3). However, for 'Key fishers', the reporting of wolfish spp. was rather inconsistent among years, for instance from 2021–2023, they were only reported in management area 1Bb, albeit from a few events. Atlantic cod was the most frequently reported fish by 'Key fishers,' with most records originating from management areas 1Bb and 1C (Fig. 5). The absence of Atlantic cod in the northernmost areas aligns with their generally lower abundance in these regions. Other fish species were reported infrequently by both 'Core fishers' and 'Key fishers.' Consequently, while the data provide some insight into the presence or absence of particular bycatch groups, interpreting broader spatial patterns is difficult and subject to uncertainty.

In conclusion, while differences in CPUE between management areas were observed, they are associated with considerable uncertainty due to limited data and variability across years. As such, it is unclear whether these differences are consistent over time or independent of natural year-to-year variability. Only for common eiders in 2021 do the bycatch numbers appear relatively robust, as data are available for all management areas, allowing both overall catch estimates and potential management area differences to be assessed. In 2021, management area 1Bb stood out with notably higher CPUE. However, in general, the differences between management areas were small and statistically insignificant when excluding 1Bb. Additional verified data are needed to determine whether this pattern holds true in other years. It is worth noting that the lumpfish roe landings in management area 1Bb in 2021 were minimal (33 t, representing just 3% of total 2021 landings). Consequently, even if the higher bycatch in 1Bb that year represents the true level, its impact on the total bycatch estimation is limited. The year 2021 also stands out due to a higher volume of bycatch reporting, which coincided with a public campaign aimed at raising awareness among fishers. This suggests that such campaigns may result in increased reporting and improved data quality.

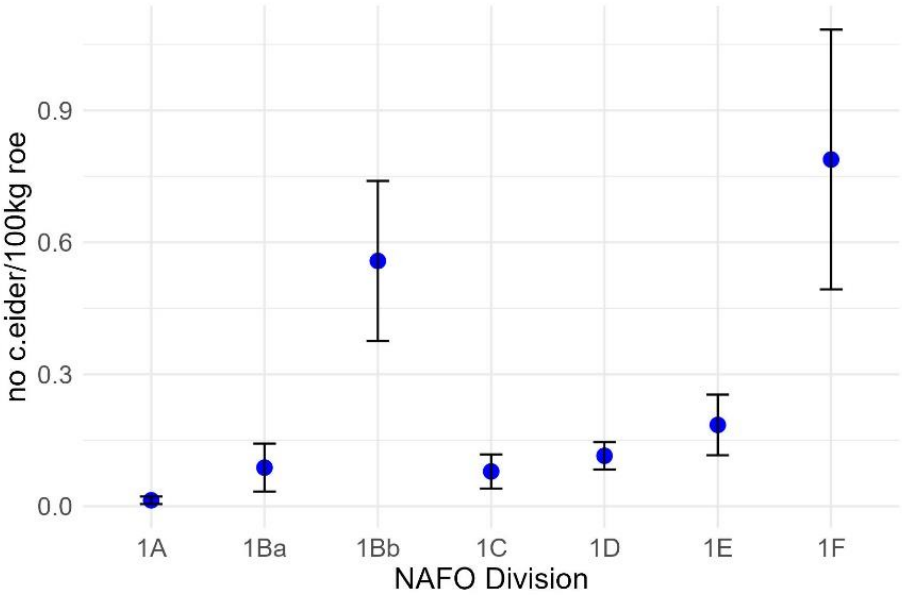

Figure 2: 'Key fishers' common eider CPUE (no/100 kg lumpfish roe) for 2016-2023 combined by management area. Bars represent standard errors.

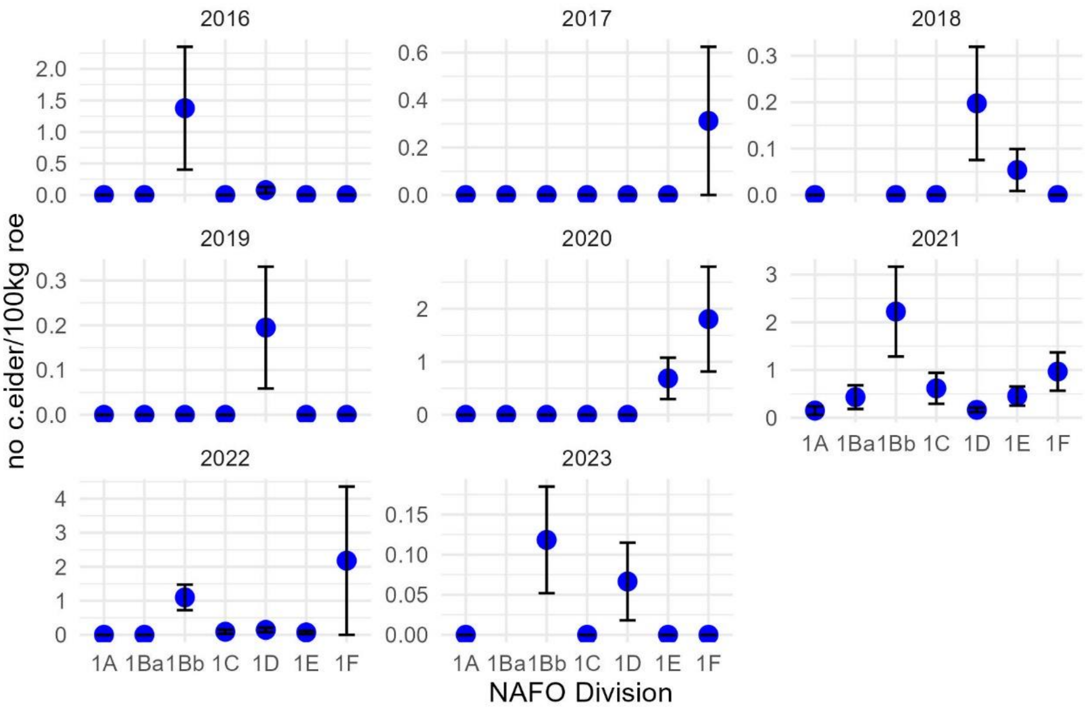

Figure 3: 'Key fishers' common eider CPUE (no/100 kg lumpfish roe) by year and management area. Bars represent standard errors.

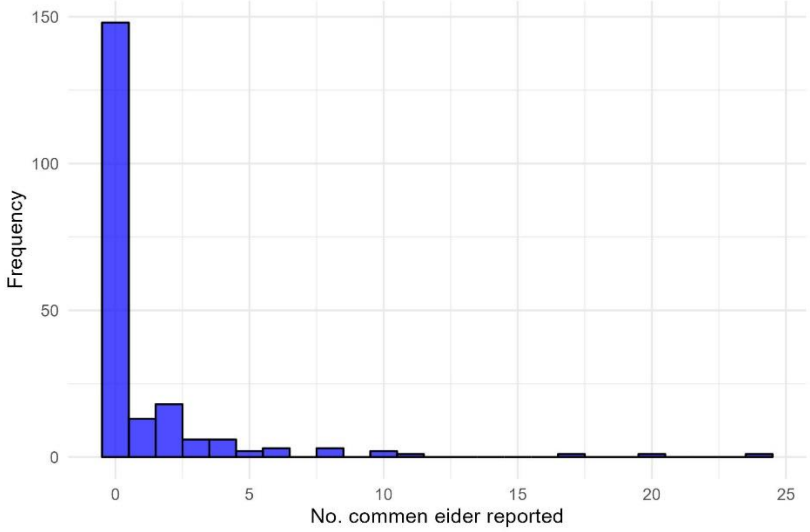

Figure 4: Histogram of the number of common eiders reported in separate landing events in 2021 by 'Key fishers'. All management areas are combined.

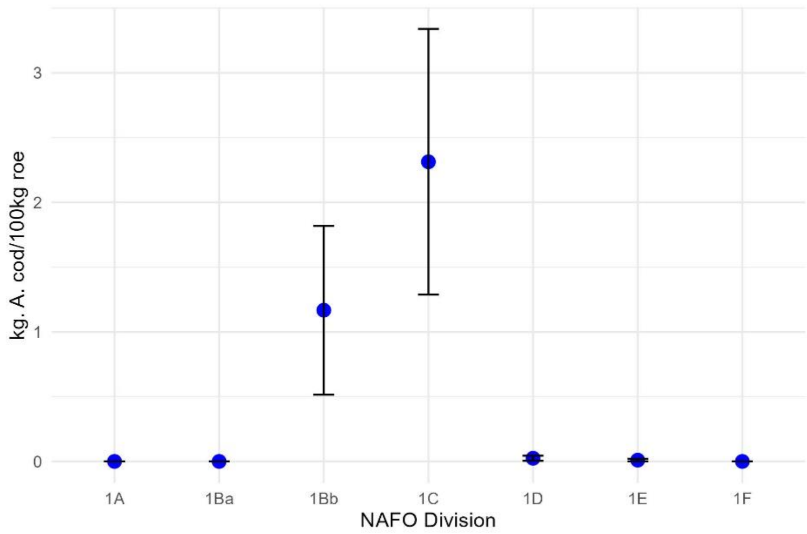

Figure 5: 'Key fishers' Atlantic cod CPUE (kg/100 kg lumpfish roe) in 2021 by management area. Bars represent standard error.

Hypothesis 3: Bycatch CPUE differs between years

This hypothesis has been partially addressed above. In most years, 'Key fishers' reported very little bycatch, with 2021 standing out as an exception, and to a lesser extent, 2022. Statistically, CPUE in 2021 was significantly different from all other years (Table 6), as was CPUE in 2022, while no significant differences were observed among other years. The key question is whether these differences reflect actual year-to-year variation in bycatch or differences in the motivation of 'Key fishers' to report bycatch. Notably, bycatch reporting prior to 2021 was virtually zero, even for common eider, which independent studies have shown to be the most prevalent bycatch group in both 2019 and 2021 (Merkel *et al.*, 2022). This strongly suggests that the observed differences are likely due to varying levels of reporting effort rather than true interannual variation in bycatch rates. The elevated reporting in 2021 coincided with a public campaign, which appears to have significantly increased the quantity and reliability of bycatch data for that year. While this may not uniformly motivate all fishers, the approach of targeted engagement, combined with consistent reminders to report, appears to have a positive influence on data collection.

*Table 5: Post-hoc Tukey test results for pairwise comparisons between years using 'Key fishers' data. The table includes estimates, standard errors, z-ratios, and adjusted p-values. An * indicates p < 0.05.*

Contrast	Estimate	SE	Z-Ratio	P-Value
year2016 - year2017	1.566	1.101	1.422	0.8475
year2016 - year2018	0.1267	0.641	0.198	1
year2016 - year2019	0.3819	0.74	0.516	0.9996
year2016 - year2020	-0.9589	0.54	-1.776	0.6367
year2016 - year2021	-3.0307	0.485	-6.25	<.0001*
year2016 - year2022	-2.1973	0.493	-4.453	0.0002*
year2016 - year2023	-0.9192	0.6	-1.532	0.7902
year2017 - year2018	-1.4393	1.101	-1.308	0.8963
year2017 - year2019	-1.1841	1.16	-1.021	0.9715
year2017 - year2020	-2.5249	1.044	-2.419	0.2319
year2017 - year2021	-4.5967	1.017	-4.521	0.0002*
year2017 - year2022	-3.7633	1.022	-3.681	0.0057*
year2017 - year2023	-2.4852	1.077	-2.307	0.2896
year2018 - year2019	0.2552	0.739	0.345	1
year2018 - year2020	-1.0856	0.538	-2.018	0.4696
year2018 - year2021	-3.1574	0.482	-6.545	<.0001*
year2018 - year2022	-2.324	0.493	-4.715	0.0001*
year2018 - year2023	-1.0459	0.599	-1.747	0.6564
year2019 - year2020	-1.3408	0.65	-2.062	0.4398
year2019 - year2021	-3.4126	0.605	-5.643	<.0001*
year2019 - year2022	-2.5792	0.616	-4.189	0.0007*
year2019 - year2023	-1.3011	0.704	-1.848	0.587
year2020 - year2021	-2.0718	0.331	-6.263	<.0001*
year2020 - year2022	-1.2384	0.352	-3.522	0.0102*
year2020 - year2023	0.0397	0.49	0.081	1
year2021 - year2022	0.8334	0.256	3.256	0.025*
year2021 - year2023	2.1115	0.428	4.932	<.0001*
year2022 - year2023	1.2781	0.437	2.921	0.0684

Hypothesis 4: The bycatch CPUE changes during fishing seasons

We initially focus on the common eider, using the year 2021 as it provides the most comprehensive data. The average CPUE by date and management area is shown in Figure 6, illustrating that the fishery starts earlier in the southern areas (1C, 1D, 1E, and 1F) and later in the northern areas (1A, 1Ba, and 1Bb). The sporadic nature of common eider bycatch is evident, with many zero reports interrupted by occasional high values. Distinct temporal patterns in bycatch are also apparent. The fishery is most intensive in management areas 1C and 1D, particularly in 1C, where bycatch largely ceases by late April. A similar trend is observed in areas 1Bb, 1D, 1E, and 1F. When combining all management areas, a clear pattern emerges: bycatch is highly variable early in the season but nearly disappears after late April (Fig. 7). This seasonal trend is also observed for Atlantic cod, but not for wolffish (Fig. 8). We did not explore it for other species due to the few records of these. For common eider, the decline in bycatch CPUE aligns with the onset of spring migration, when birds leave the wintering areas to return to nesting grounds. This suggests that postponing the fishery until late April could significantly reduce seabird bycatch. However, before implementing such measures, it is crucial to investigate the seasonal development of roe quality and lumpfish roe CPUE. These factors vary seasonally due to the decline in spawning fish or the depletion of fish present in the area.

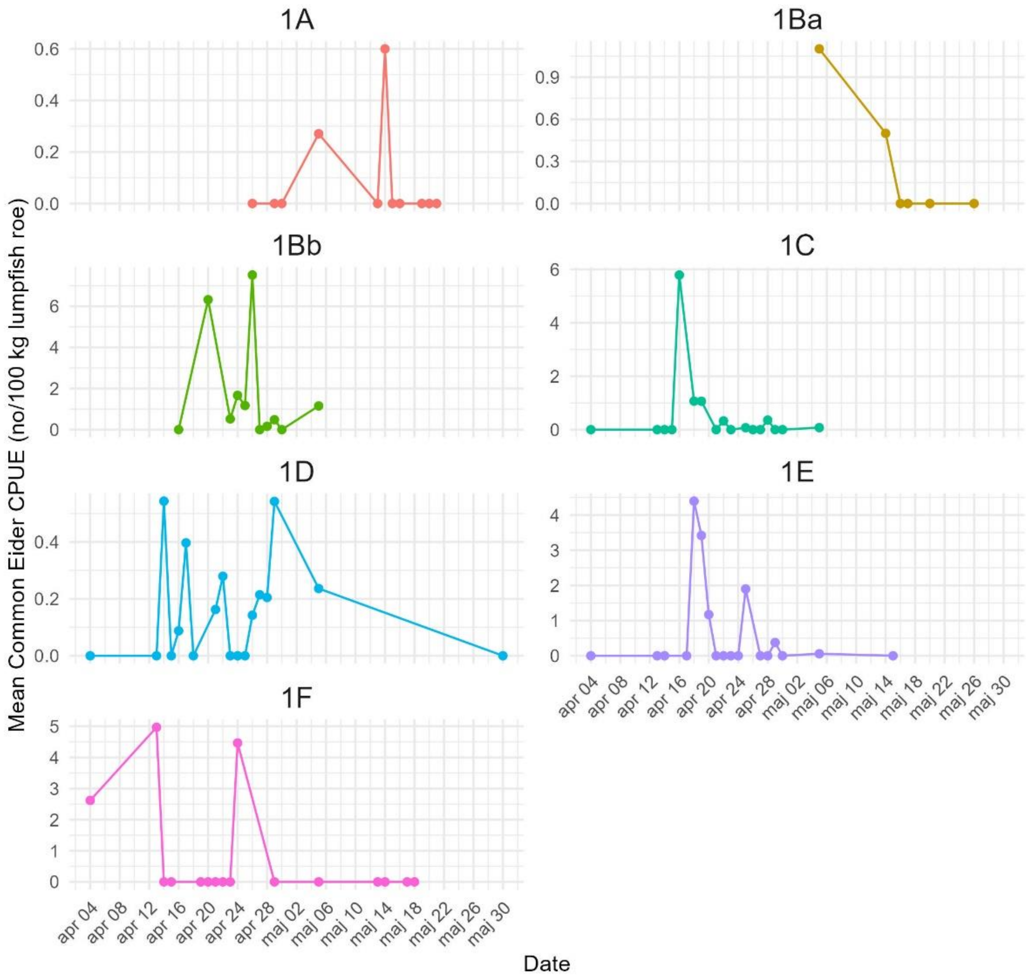

Figure 6: Average common eider CPUE (no/100 kg lumpfish roe) of 'Key fishers' in 2021 by date and management area.

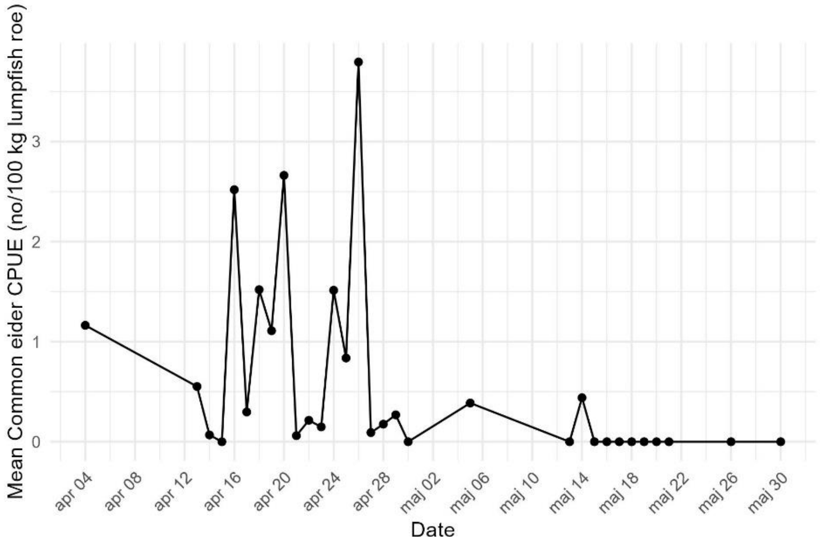

Figure 7: Average common eider CPUE (no/100 kg lumpfish roe) of 'Key fishers' in 2021 by date.

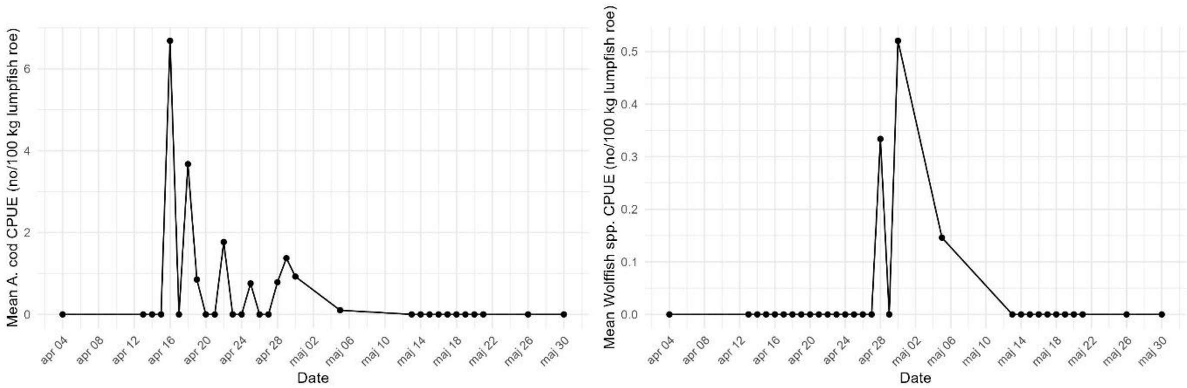

Figure 8: Average Atlantic cod (left) and wolffish spp. (right) CPUE (kg/100 kg lumpfish roe) of 'Key fisher' in 2021 by date.

Hypothesis 5: Key fisher' CPUE can provide quantitatively valid estimates of bycatch.

With knowledge on the total amount of lumpfish landed in each management area and a CPUE for bycatch groups in relation to lumpfish roe we estimate the total bycatch in each management area and year. We base this on the assumption that the mean bycatch CPUE in an area for a given species is representative for the entire fishing season and estimate the total management area bycatch as:

$$Total\ bycatch_{species} = CPUE_{Species,management\ area} * Lumpfish\ roe\ landed_{total\ landings}$$

We estimate the bycatch for 2019-2023 for the following species:

'Birds': Common eider, king eider and black guillemot (long-tailed duck was not common enough to allow for estimation)

'Fish': Atlantic cod, wolffish spp. and Atlantic halibut.

'Mammals': Ring seal

To estimate the variability of bycatch estimates, we calculate 95% confidence intervals (CIs) for the mean catch per unit effort (CPUE) using the formula:

$$CI = mean \pm 1.96 \times (SD / \sqrt{n})$$

In this formula, the mean refers to the sample mean of the CPUE. 1.96 corresponds to a 95% confidence level, based on the standard normal distribution. SD is the standard deviation and n is the sample size.

Due to the rarity of bycatch events (or at least the reporting), the uncertainty associated with the CPUE estimates is high. Common eider is the most significant bycatch species; however, 2021 and 2022 appear to be the only years where the estimates provide a potentially accurate picture of bycatch. In other years, the data are dominated by most management areas having no recorded bycatch. The estimated common eider bycatch across all of Greenland was 5,238 individuals [95% CI: 476–10,337] in 2021 and 2,479 individuals [210–6,292] in 2022 (Table 7). Other bycatch groups are also most prominent in 2021 and 2022, with the exception of Atlantic cod, which shows significant bycatch in most years (Table 8). This consistent reporting of cod is likely influenced by its commercial value. As there is no increased incentive to report common eider more frequently compared to other non-commercial species, it suggests that species not present in significant numbers in 2021 are likely not regularly caught in this fishery. Consequently, species such as long-tailed duck, seals, and harbor porpoise are unlikely to represent relevant bycatch.

The 2019 and 2021 bycatch estimates for management area 1D were compared with estimates from Merkel et al. (2022), who based their estimates on in situ observations of bycatch in roughly the same area. Their individual data points are highly accurate, but the uncertainty arises from a smaller sample size, which limits the documentation of rare events. In contrast, the fishers' bycatch data presents the opposite situation, with a more comprehensive dataset, but less precise individual data points. Nevertheless, the two independent sources of information provide comparable estimates and can be used either to build confidence in the estimates or to highlight potential discrepancies. Merkel et al. (2022) estimated common eider bycatch in management area 1D to be 3,612 [631−10,799] birds in 2019 and 2,285 [293−6,961] birds in 2021. The estimates based on 'Key fishers' fall at the lower end of these confidence intervals (Table 7), suggesting that the 'Key fisher' 2021 estimate of 498 [189-808] birds should be considered a minimum estimate. The upper limit of the 95% confidence interval for 2019 in our study 583 [0-1401] also overlaps with the Merkel et al. (2022) estimate, further supporting the notion that 'Key fisher' represent minimum estimates.

Table 7: Estimates of 'Bird' bycatch (in numbers) using 'Key fisher' CPUE (mean [95% CI]) and total lumpfish roe landings. Values are count values.

Year	Management area	Common eider	King eider	Black guillemot
2019	1A	0	0	0
	1Ba	0	0	0
	1Bb	0	0	0
	1C	0	0	0
	1D	583 [0-1401]	0	0
	1E	0	0	0
	1F	0	0	0
Total		**583 [0-1401]**	**0**	**0**
2020	1A	0	0	0
	1Ba	0	0	0
	1Bb	0	3 [0-8]	0
	1C	0	0	0
	1D	0	0	0
	1E	1578 [0-3386]	0	0
	1F	1170 [0-2452]	0	0
Total		**2748 [0-5838]**	**3 [0-8]**	**0**
2021	1A	219 [0-495]	38 [0-101]	24 [0-64]
	1Ba	542 [0-1246]	0	265 [0-864]
	1Bb	752 [99-1405]	0	9 [0-27]
	1C	1785 [0-3686]	0	0
	1D	498 [189-808]	0	0
	1E	693 [69-1317]	0	0
	1F	749 [119-1380]	0	0
Total		**5238 [476-10337]**	**38 [0-101]**	**298 [0-955]**
2022	1A	0	0	0
	1Ba	0	0	0
	1Bb	563 [178-948]	0	1 [0-2]
	1C	320 [0-781]	0	0
	1D	443 [32-854]	0	0
	1E	125 [0-312]	0	0
	1F	1028 [0-3397]	0	0
Total		**2479 [210-6292]**	**0**	**1 [0-2]**
2023	1A	0	0	0
	1Ba	0	0	0
	1Bb	81 [0-173]	0	0
	1C	0	0	0
	1D	202 [0-513]	0	0
	1E	0	0	0
	1F	0	0	0
Total		**283 [0-686]**	**0**	**0**

Table 8: Estimates of 'Fish' and ring seal bycatch using 'Key fisher' CPUE (mean [95% CI]) and total lumpfish roe landings. Values are expressed in kilograms for fish and in counts for ring seals.

Year	Management area	Atlantic cod	Wolffish spp.	Atlantic halibut	Ring seal
2019	1A	0	0	0	0
	1Ba	0	0	0	0
	1Bb	0	0	0	0
	1C	0	0	0	0
	1D	0	3662 [0-9990]	743 [0-2239]	0
	1E	0	0	0	0
	1F	0	0	0	0
Total		**0**	**3662 [0-9990]**	**743 [0-2239]**	**0**
2020	1A	0	0	0	0
	1Ba	0	0	0	0
	1Bb	0	0	0	0
	1C	394 [0-1193]	89 [0-269]	0	0
	1D	0	0	0	0
	1E	2511 [0-6416]	0	0	0
	1F	496 [0-995]	122 [0-367]	471 [0-1415]	0
Total		**3401 [0-8604]**	**211 [0-636]**	**471 [0-1415]**	**0**
2021	1A	0	0	0	30 [0-94]
	1Ba	0	0	0	0
	1Bb	395 [0-847]	126 [0-251]	16 [0-49]	8 [0-23]
	1C	6710 [697-12722]	0	0	0
	1D	74 [0-195]	0	0	0
	1E	15 [0-46]	0	0	29 [0-89]
	1F	0	0	0	33 [0-88]
Total		**7194 [697-13810]**	**126 [0-251]**	**16 [0-49]**	**100 [0-294]**
2022	1A	0	0	0	0
	1Ba	0	0	0	0
	1Bb	5733 [610-10857]	3613 [0-7242]	1273 [75-2470]	0
	1C	3437 [814-6059]	657 [0-1598]	0	0
	1D	13 [0-39]	201 [0-501]	242 [0-561]	0
	1E	0	0	0	0
	1F	130 [0-431]	0	0	51 [0-170]
Total		**9313 [1424-17386]**	**4471 [0-9341]**	**1515 [75-3031]**	**51 [0-170]**
2023	1A	0	0	0	0
	1Ba	0	0	0	0
	1Bb	469 [83-854]	0	0	5 [0-14]
	1C	2499 [0-6825]	0	0	0
	1D	332 [0-1036]	0	0	0
	1E	0	0	0	0
	1F	0	0	0	0
Total		**3300 [83-8715]**	**0**	**0**	**5 [0-14]**

Conclusions

In conclusion, we argue that 'Key fisher' data can, in some cases, provide credible estimates of bycatch, as they report bycatch at a much higher frequency than 'Core fishers'. However, there are clear reservations regarding the accuracy and consistency of these data. A concerted effort is needed to educate fishers about the importance of bycatch reporting, with continuous education to ensure it remains a priority. This necessity is highlighted by the sparse reporting prior to 2021, when a reporting campaign was introduced, and the gradual decline in reporting during 2022 and 2023 as the campaign's influence diminished.

Systematic independent studies are required to verify the bycatch estimates, ideally conducted across different management areas. Given the impracticality of independently monitoring every fisher's bycatch and reporting - due to the large number of fishers, the extensive coastline, and the relatively short fishing season - it is evident that relying solely on independent studies for verification would be resource-intensive and inefficient. As such, a systematic approach to collecting data from 'Key fishers' appears to be a more viable method for estimating bycatch and should be pursued by the relevant authorities.

As demonstrated, there are inherent limitations in the conclusions drawn from the current dataset. The bycatch estimates derived from 'Key fisher' data can only, and to some degree, be used quantitatively for the more common bycatch species, such as common eider, Atlantic cod, and wolffish spp. However, it is evident that even 'Key fishers' may underreport bycatch, underscoring the need for continued efforts to improve data accuracy and reliability. While rarer bycatch groups are insufficiently represented for reliable quantitative estimation, the data remain valuable for examining spatial patterns, including those for more commonly caught species. For instance, the near absence of black guillemot in the southern management areas highlights such spatial insights. In addition to identifying geographic patterns, 'Key fisher' data can help form an overall assessment of species likely not at risk from the lumpfish fishery. Examples include long-tailed duck, harbour porpoise, and Greenland shark, which appear negligible in terms of bycatch. By combining spatial insights with qualitative assessments, these data can support more informed and regionally tailored management decisions.

Acknowledgement

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